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DISCUSSION OF FINAL FOUNDATION TREATMENT AT HOOVER DAM

(Published in December, 1951)

By James B. Hays, V. L. Minear, Byram W. Steele, William H. McAlpine, Fred H. Lippold, O. E. Boggess, H. Cambefort, and A. Warren Simonds

SOIL MECHANICS AND FOUNDATIONS DIVISION

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DISCUSSION

JAMES B. HAYS,[4] M. ASCE.—The writer was fortunate enough to be familiar with the field work during the early stages of grouting under the base of Hoover Dam. The treatment of the sides in canyon walls was done later. Although it is easy to criticize afterward, the writer thought in his own mind, at the time, that the abutment grouting should have been extended to meet a ring-grouted cutoff curtain in each of the tunnels. If this had been done, each of the tunnels should have been grouted solidly all around for their full length upstream from the main curtain. Downstream from the main cutoff curtain drain holes would have been included. Such treatment might have taken care of a large part of the leakage that developed later. However, it would not have solved all the problems. The right abutment was the source of a hot water supply that undoubtedly would have been affected by the reservoir when filled.

The drainage wells in the dam immediately downstream from the grout curtain were probably mostly in the grouted zone and not in the open rock where they should be to relieve upward pressure. The paper indicates this and explains how the problem was corrected. It has long been the writer's opinion, since the completion of Hoover Dam that, in many cases, a general all-over drainage system is desirable under high concrete dams. Special attention must be given to drainage of known faults, seams, joints, or other water-carrying zones.

Some interesting facts concerning the effects of high-pressure grouting at Hoover Dam came to the writer's attention. The lower system of contraction joints had been grouted to about 200 ft from the base of the dam, using pressures limited to about 50 lb per sq in. The joints had copper seals to divide the work into 50-ft lifts and into two sections upstream and downstream. There was also a seal at the bottom just above the rock. The high-pressure foundation grout broke through the bottom seal and followed up the contraction joints that had already been grouted, for a considerable height.

The upstream toe of the dam had a shelf of concrete, or spread footing, projecting over the rock. At one point where it was about 10 ft thick the high-pressure grouting of a C-hole actually split the concrete. The author could possibly elaborate on this phase and give the correct data.

The grouting system provided for the abutments was neither protected by seals nor divided into sections, as were the contraction joints. Hence, there was difficulty in keeping the grouting pipes and tubes from being plugged when leakage developed from the foundation. It is understandable why the decision was made at the time to limit the foundation grouting on the abutment to avoid plugging the abutment contact grouting. Present hindsight judgment suggests that low-pressure consolidation grouting over the abutments would

NOTE.—This paper by A. Warren Simonds was published in December, 1951, as *Proceedings-Separate No. 109*. The numbering of footnotes in this Separate is a continuation of the consecutive numbering used in the original paper.

[4] Chf. Engr., Kenney Dam, Nechako, B. C., Canada (British Columbia International Eng. Co. of Vancouver, B. C., Canada).

have corrected this. In the case of Hoover Dam, it would have been a difficult job due to the steepness of the walls. After the concrete was in place the high-pressure grouting could have been completed. The drainage holes would have had to be deep enough to penetrate well behind the consolidated zone and at the same time well outside the high-pressure grout curtain.

The author's description of the re-grouting and re-drainage work is quite clear to one who was familiar with the general geology of the dam site and furnishes answers to practically all the questions that would arise. The conditions are different at all dam sites. Each location is a problem in itself. Grouting is usually started from a basic pattern. As the work proceeds, a day by day study of the "take" or results determines whether additional work is needed or not. The geology must be studied as thoroughly as possible in order to produce the desired results.

The Hoover Dam experience, as well as that of some other dams, reveals the fact that the foundation treatment problem is frequently a much larger problem than is ordinarily visualized.

In some types of dams a certain amount of controlled leakage that will not harm the structure is permissible. Flood-control dams would fall in this category. In others, where the value of water is high, the allowable leakage is small. However, in all cases the leakage should be handled through an adequate drainage system.

V. L. MINEAR,[5] M. ASCE.—This is a unique and valuable paper. It is unique, in that where the average paper glosses over or ignores mistakes, this paper points to certain rather serious errors in design and construction procedure, together with the measures taken to correct them. It thus offers a valuable opportunity to examine some of the present-day practices in the light of experience in the Bureau of Reclamation (USBR) over a period of twenty years on this dam.

Hoover Dam was designed and constructed when "***the available information on existing foundation conditions was inadequate." During the years that have elapsed, the science of engineering geology has made great strides in the field of foundation exploration. This has taken much of the guesswork out of foundation grouting and drainage. Modern practice consists of a program whereby the original grouting design, based upon the general information obtained during preliminary investigations, is modified in accordance with information which becomes available as construction progresses. Thus, after the site has been dewatered and the foundation rock exposed by stripping, the surface is cleaned meticulously so that surface manifestation of subsurface defects can be seen, measured, mapped, and studied. Thereafter grout holes are drilled into the rock end to end of the dam at close intervals along the cutoff. These holes are then pressure tested, pressure washed, and pressure grouted under the strictest control and with a complete record kept of the behavior of the foundation under known conditions. Moreover, it is common practice to put down additional core drilled exploratory holes in questionable areas. It has been found that, if these data are collected and

[5] Engr. (Foundations), Office of the Chf. of Engrs., Dept. of the Army, Washington, D. C.

analyzed as they become available, any engineering geologist who is "worth his salt" will have a detailed knowledge of subsurface conditions and will be in a position to give valuable advice to the construction forces. This goes far in eliminating the necessity for making important decisions on a trial-and-error basis. The employment of a competent full-time resident geologist costs money, but it has been found to be cheaper and more satisfactory than making "***a systematic exploration of the foundation*** by drilling BX-size core holes, in an attempt to find where defects in the foundation rock existed" (see under the heading, "Plans and Preparation for Corrective Measures") under completed dams showing signs of distress.

"The increasing uplift pressure on the base of the dam was of gravest concern to the engineers responsible for the safety of the structure." (See under the heading, "Increase in Uplift Pressure on Base of Dam.") Dams are being built, even today (1952), without provisions for making observations on the pressure acting on their bases. Uplift is an important consideration in the design of dams, yet actually little is known concerning how it developes, its intensities, and how and where it acts. Consequently, arbitrary assumptions are used in design. These easily can be in error in any specific case due to unknown or but partly understood subsurface conditions, faulty grouting, leaching out of an originally tight curtain, or clogging of drain holes as time passes. The forces actually acting at any given time are the ones that are of real importance. These forces are easily and cheaply determined and their magnitude compared with design assumptions, by installing and reading uplift gages as described by K. B. Keener,[6] M. ASCE. By means of the gages, ample warning is given so that remedial measures can be taken in time should that become desirable. Had the USBR failed to install such gages in Hoover Dam and failed to make systematic reading thereon, the dangerous condition which developed might not have become known until possibly too late.

> "Because of the inaccessability of the leaks it became necessary to abandon the grouting of the leaking holes rather than take the risk of fouling the grouting systems of the abutment joints. This procedure left gaps in the cutoff curtain through which percolation developed." (See under the heading, "Inadequacy of Original Grouting.")

It is not unusual to see present-day design showing gravel drains located in close proximity to areas which are to be pressure grouted. Pressure grouting, properly done, searches out any openings existing nearby and fills them with grout. Consequently, when grouting is begun, it frequently happens that hole after hole breaks into the drains. It is common practice under such conditions to thicken the grout and wash out the drains. The former is an euphemism for "kill the hole," and the latter is easier said than done. The result too often is that neither an effective drainage system nor a grout curtain is provided. Scheduling construction operations so that grouting precedes the placement of gravel, or substituting drain holes drilled after the grouting is finished, avoids this difficulty.

[6] "Uplift Pressures in Concrete Dams," by Kenneth B. Keener, *Transactions*, ASCE, Vol. 116, 1951, p. 1218.

> "On the Nevada abutment * * * several grout holes had penetrated a fault zone, and 4 grout holes in this area were abandoned, chiefly because of excessive quantities of grout that had been injected into them." (See under the heading, "Inadequacy of Original Grouting.")

The treatment that should be given a hole that takes an exceptionally large quantity of grout is debatable. It is the writer's opinion that foundation problems should be solved at the time of construction and, moreover, that abandoning or deliberately choking a hole which penetrates a leaking zone is no solution of the problem. It merely postpones the "evil day." Grouting, to stop leakage or reduce uplift after the dam is in service, is a most discouraging experience. The rock generally is so saturated with water that the grout travels widely and there is no way to prevent it. Furthermore, not only does the flowing water carry away much of the grout, but there is also a tendency to build up a barrier near the toe, in the very area where free drainage is most desirable. This behavior makes grouting beneath a dam with full reservoir a hazardous undertaking unless uplift gages are available to serve as guides to changes in the distribution and intensities of uplift which accompany grout injection. These changes can be rapid and of alarming proportions. Because of the possibility of these and other serious consequences, it is felt that engineers should have more valid reasons for abandoning a hole than some preconceived notion of the amount of grout that it should take. This is not to say that the endless pouring of neat cement down a hole is advocated. When the formation is such that large grout "takes" are anticipated, specifications should provide for the use of fillers such as sand, bentonite, rock flour, flyash, or even clay, in preference to simply abandoning the hole and hoping for the best.

In effect, this paper is a case history of the progress made in the "art" of pressure grouting during the period elapsed since 1930. As such, it merits the closest study by those engineers interested in the design and construction of this highly specialized work.

BYRAM W. STEELE,[7] A. M. ASCE.—The entire program of foundation treatment for Hoover Dam is summarized in this paper in a way that should be very helpful in the foundation treatment of future dams regardless of size.

During the construction period it is not always possible to complete a finished program of foundation grout treatment. This fact should be obvious, but if it is, it is ignored in most cases; and, likewise, in most cases adequate provision for future grouting is not made at the time the construction of the dam is nearing completion.

Hoover Dam is a "near ideal" in regard to the manner in which foundation investigation and treatment were handled over a long period of years. This class of work is not readily accomplished by contracts because of the many elements of uncertainty that are continually arising which demand changes in procedure not readily made under contract specifications.[8] Foundation investigation and the later foundation treatment should be done by force account.

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[7] Cons. Engr., Arlington, Va.

[8] "Treatment of Foundations for Large Dams by Grouting Methods," by A. W. Simonds, Fred H. Lippold and R. E. Keim, *Transactions*, ASCE, Vol. 116, 1951, p. 548.

rather than by contract, and it should be done by engineers who are familiar with conditions at the site of the work during construction. There are relatively few dam projects of any magnitude that cannot afford a drilling and grouting unit specially designed for this type of work, and a crew of experienced men to operate it until foundation treatment has been satisfactorily completed.

There is another phase of the grouting problem that is worthy of careful consideration. It is the necessity for the services of an experienced geologist in the early stages of the investigation and also during the grouting operations. A geologist who has had considerable experience in dam foundation treatment can contribute much to the success of the job by virtue of his knowledge of geological formations. Such knowledge is not usually possessed by civil engineers.

The writer would like to suggest that foundation treatment for future dams of any magnitude be set up on a force account basis rather than on a contract basis, and also that experienced foundation engineers be employed early in the pre-construction stage and then retained until all post-construction foundation treatment has been completed. In too many instances the foundation treatment is handled by inexperienced men with such equipment as is available on the job, with the result that effective treatment is not accomplished.

Last but not least, there is no easier way to waste time and money than by pumping cement grout into a hole in the ground without adequate checks on where the grout is going and whether it is doing any good. Here is where the geologist's knowledge of foundation formations is valuable. It can be used to excellent advantage in planning a well-coordinated program for all phases of the drilling and grouting; and it will be valuable later, when interpreting the diamond-drill cores of a few typical areas to see whether the penetration of grout anticipated has been accomplished, and whether the grout in the cracks and crevices is dense and impervious, or porous and chalky.

WILLIAM H. McALPINE,[9] HON. M. ASCE.—A frank and quite complete description is presented of the many problems connected with grouting and foundation treatment required to reduce uplift pressures and leakage of the dam to reasonable safe proportions. It should be very helpful to the many engineers and geologists engaged in the design and construction of dams on rock foundations, especially the higher dams on the poorer rocks. It may be regarded as a sequel to papers by other authors.[10,8,6]

The author does not indicate what uplift assumptions were made in the design of the dam, but it is quite evident that the depths of grout curtain and drainage wells were quite inadequate for the character of the foundation and height of the Hoover Dam. Since the construction of this dam was first begun there has been a great impetus in the construction of many high dams by government agencies who employ large engineering organizations including specialists, and outside consultants from time to time. As a result there has

[9] Chf. Engr., Office of the Chf. of Engrs., Dept. of the Army, Washington, D. C.

[10] "Correction of Reservoir Leakage at Great Falls Dam," by A. H. Weber, *Transactions*, ASCE, Vol. 116, 1951, p. 31.

been a decided advance in the "art" of subsurface explorations and foundation treatment, including grouting and drainage. Nevertheless a carefully planned foundation treatment frequently must be modified during construction because of conditions not fully disclosed by the borings.

Finally, it seems possible that the knowledge to be gained from the uplift observations made on numerous dams may lead to some economy in design.

FRED H. LIPPOLD,[11] M. ASCE.—The problems and complications involved in an adequate treatment of the foundation of a high masonry dam are presented admirably in this paper. No "rule of thumb" method can be used in designing a foundation grouting and drainage treatment program; each foundation has its individual problems that can, and do, vary as much as the individual geologic formations at different sites. Minor faulting and zones of shearing at different locations would have affected, materially, the grouting program at Hoover Dam. The paper also shows the desirability of a thorough foundation treatment program during initial construction to alleviate the probability of additional treatment at some later date.

Of particular interest to the writer was the number of holes that were abandoned during the initial grouting program. It is realized that even under ideal conditions it is occasionally necessary to abandon grouting any hole because of excess leakage, but the percentage at Hoover Dam seems high. Subsequent inability to regrout the zone by reopening the same hole would tend to prove the theory that the most effective way to grout any open zone or seam is through the first hole connecting to it. Although there may be a limit to the volume of cement that should be injected into any one hole, the total is indeterminate unless it is known exactly where the grout is going. Certainly such a limit would be high. Adjacent holes just a few feet away often miss the seam or intersect it where it is tight, with the net result that an excessive amount of drilling is required to complete the job.

Much was learned about both the design and technique of foundation treatment at Hoover Dam, and on more recent construction the initial treatment is far more complete. However, due to peculiar geologic conditions it could still be necessary to perform some additional work after a dam is in operation. Based on this realization, pipes for grouting are usually spaced at 5-ft centers along the foundation gallery even though it is contemplated that such close spacing may not be required by the method of closures during the initial construction. The unused pipes can be used for additional treatment if softening of seams, foundation deflection, or some other latent foundation defects appear after the reservoir is filled.

It is seldom, if ever, possible to create a grout curtain that will not allow a small amount of percolation. The drainage holes are designed to pick up these flows and relieve the uplift pressure. However, the drainage holes (like grout holes) can fail to intersect seams or can cross them where they are locally tight. Where flow from foundation drains is not high, additional drainage holes often effectively reduce the uplift at a nominal cost. This method of uplift relief has

[11] Engr., Bureau of Reclamation, U. S. Dept. of the Interior, Denver, Colo.

been used on two USBR dams of medium height in recent years. The great difference in cost dictates that this method should be studied thoroughly before an extensive supplemental grouting program is begun. Where seepage flows are high (such as they were at Hoover Dam) additional grouting is called for but in addition the supplemental drainage-hole pattern was probably much more effective than the original one.

The paper also shows the need of extensive foundation treatment in the case of an extremely high dam even where the foundation is relatively good. A less competent foundation might not have been susceptible to successful treatment by pressure-grouting methods alone. The quantity of water flowing from some of the holes effectively shows that when cutoff drifts or shafts may be required, they must be built before the reservoir is filled. The problems of pressure grouting a foundation under full reservoir head are complex, as well as costly. There must have been many difficult problems in performing the actual operation. It is gratifying to know, however, that even under such adverse conditions, pressure grouting and drainage were capable (although admittedly costly) of relieving the undesirable conditions.

O. E. BOGGESS[12].—An excellent presentation of factual data on foundation problems at Hoover Dam and their ultimate solution is contained in this paper. The necessity for extensive additional grouting, as outlined by the author, demonstrates the importance of a thorough job of foundation treatment during construction. Regrouting of the foundation of a dam, particularly a high dam, after the reservoir has filled and the dam is in operation, presents a difficult and expensive operation. As engineer in charge of the work at the site, the writer observed first hand the problems encountered during the regrouting of Hoover Dam.

Many of the holes carried large flows of water under high pressure (150 lb per sq in. to 200 lb per sq in.). This condition made drilling much more difficult and hazardous than usual. In addition to slowing down the drilling speed, the threat that drill rods would become free and plunge out of the hole under the heavy flow and high pressure was always present.

In one instance, during the drilling of a horizontal hole, a slip of a wrench caused 400 ft of drill rods to come out of the hole as if they had been shot out of a cannon. Fortunately the only casualty was a mangled mass of drill rods. Only experienced and seasoned drillers were used on this work.

The problem of unobserved grout leaks into the reservoir did not prove serious at Hoover Dam. The tendency of the grout to follow the line of least resistance in a downstream direction was often noted by an increase in the uplift pressure gages throughout the dam. The direction of the grout travel and the extent of the area being grouted was well indicated by the action of the uplift gages. In most instances where the uplift gages showed an increase in pressure during grouting, the readings decreased to somewhat below the original reading after the hole was completed. The back pressure at the collar of the hole was checked periodically during grouting. When back pressure was near reservoir head at the elevation of the hole and remained stationary, it was

[12] Engr., Bureau of Reclamation, U. S. Dept. of the Interior, Denver, Colo.

suspected that grout was leaking into the reservoir. As a final determination, air was forced into the hole and the reservoir surface was watched for air bubbles. If air bubbles showed through the reservoir, the grout mixture was gradually thickened until the hole sealed off. It is believed that very little grout was lost through leaks into the reservoir.

Relatively thin grout mixtures were used in the regrouting at Hoover Dam. After experimenting with various mixes, it was found that even holes that accepted water freely would plug prematurely after a few sacks had been injected unless a starting mixture of thin grout was used. In leaks that were observed a considerable distance from the hole, it was often noted that the water-cement ratio (w/c) of the grout at the leak was much lower than that of the grout being injected. This indicated that the water was being forced out of the grout as it traveled through the rock. Since this condition existed after the reservoir filled and the foundation rock had become saturated, it would appear that even thinner mixes would be necessary during construction when the foundation rock was comparatively dry. The author mentions hole A-124 in the Arizona abutment that accepted a total of 8,258 sacks. This hole was started with a w/c of 10:1. During the injection of the first 100 sacks the w/c was gradually reduced to 6:1. Several attempts were made to reduce the w/c to 5:1 as the grouting progressed, but each time the hole showed signs of tightening up and the w/c was changed back to 6:1. The grouting of this hole had a widespread effect in drying up the Arizona abutment, particularly in the upper penstock tunnel.

There were many interesting problems during the course of the operation but by continued efforts they were overcome and in retrospect appear minor. The final result is proof of the effectiveness of the program, and the foundation conditions must have been materially improved.

H. CAMBEFORT[13].—This extremely interesting paper illustrates how an initial deficiency in tightness and drainage of the foundation has been successfully remedied.

The French engineer who specializes in this kind of work, and is accustomed to foundations of dams consisting of cracked limestone, is astonished to discover that the depth of the cutoff curtain of Hoover dam was determined by a statistical study of the depths of grout curtains established at other dams, and that a reconnaisance of the foundation was made only for corrective purposes. Such a method may be justifiable for dams on rivers whose bed is alluvial, but not for large dams founded on rock. In this case the subterranean water circulates in the cracks or joints of the rocks at great depths, causing uplift pressures or high leakage flow.

The science of geology provides no means of determining the depth to which grout should be forced. Only an investigation by core drilling with clear water and water testing, as the hole is deepened, can be accepted as precise. These water tests are performed by placing a cap below a test section of about 5 m (16.4 ft) in the foundation drill hole. Clear water is pumped into this section. A manometer indicates the pressure, and a meter indicates the volume of water

[13] Civ. Engr., School of Bridges and Highways; Prof. of Soil Mechanics at the School of Public Works, Paris, France.

injected during a fixed time—in general equal to 10 min. The unit pressures are progressively increased up to 2, 4, 6, 8, . . . kg per sq cm, for example; and the tests must be completed in decreasing the pressures in the same sequence—8, 6, 4, 2 kg per sq cm.

The flow curve, plotted as a function of the pressure, provides ample indications of any cracking in the rock. Eventually, it leads to the evaluation of the coefficient of permeability of a pulverulent soil which is equivalent to the broken rock. Thus, the extent of the leakage can be computed from the leakage itself.

When the water test of a section is finished, the cement is injected, thus providing a way to interpret the subsequent tests; and, at the same time, the procedure assists in determining the magnitude of cement absorption necessary to tighten the broken rock mass.

Experience indicates that it is uesless to inject grout into rock in which the absorption, in the course of tests, is not more than 1 liter per min per m (0.08 United States gal per min per ft of hole) under a pressure of 10 kg per sq cm (142 lb per sq in.)—the test lasting 10 min. The equivalent coefficient of permeability is of the order of 10^{-7} m per sec (3.28×10^{-7} ft per sec). These criteria have been established by Maurice Lugeon,[14] in relation to dams more than 30 m (98.4 ft) high. For lower dams, one can be content with 0 maximum of 3 liters per min per m (0.24 United States gal per min per ft of hole). Criteria such as these, which eliminate all personal factors, are certainly better than those that consist merely of obtaining a core sample of sound rock 1.50 m (4.92 ft) long. The fixed injections are always made on sections or stages about 5 m (16.4 ft) long to avoid the sedimentation of cement which occurs in longer sections and which seals the entrance to the cracks before they can be grouted. Such injections can be made as the drilling advances, from top to bottom; they can be made in reverse order, from bottom to top, which plainly separates the operation of drilling from that of grouting.

Before beginning the injection, a brief test of water pressure is made to clean the cracks and to determine the proportions of the grout to be used at the outset. During the injection, if the pressure does not increase, the engineer increases the proportions of the grout progressively (that is, he reduces the water-cement ratio).

The very large cracks are closed quickly with a mixture of cement, clay, silicate of sodium and water, which is a thixotropic mixture and is intended not to penetrate very far. Thereafter, ordinary cement grouting is completed. Cleaning of cracks as practiced at Hoover Dam sometimes yields good results, but not always. Finally, the spacing of the injection bore holes (grout holes) is determined by a preliminary test involving two or three bore holes with a control hole in the center. The variations in the quantities of cement injected supply an index of the modification required of the spacing selected for the test.

These procedures (used in France for several decades) utilize the same principles as those used in the United States, but they differ in details as stated herein.

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[14] "Barrages et géologie," by Maurice Lugeon, Dunod, Paris, France, 1933, p. 87.

A. WARREN SIMONDS,[15] M. ASCE.—The question that so often arises in grouting the foundations of dams—whether the program of treatment, as designed, will be adequate, inadequate, or more than adequate—is raised indirectly by Mr. Hays. The most opportune time for providing adequate treatment of the foundation is during the construction period. However, one cannot be sure of the adequacy of the foundation treatment until after the reservoir has filled and seepage or leaks begin to develop. If the curtain grouting at Hoover Dam had been extended during construction to meet the ring-grouted cutoffs in each of the tunnels (as mentioned by Mr. Hays), the foundation conditions would have been improved, but it is probable that some additional work would have been required later.

As Mr. Hays points out, the drainage holes should be placed a sufficient distance downstream from the grout curtain to penetrate ungrouted rock. After the small seams in the rock have been partly blocked by grout, holes drilled in such an area are rarely as efficient for drainage purposes as those drilled in ungrouted rock. When the high uplift pressures were first noticed, an attempt was made to control this pressure by drainage only. A few holes were drilled in strategic places to lower the uplift pressure; but the discharge from them was so great that it taxed the capacity of the sump pumps within the dam. It was then decided to procede with the additional grouting in order to reduce the flow of water through the foundation. The drainage holes drilled subsequent to the grouting program were effective in reducing the uplift pressure with only a nominal discharge.

The occasionally-observed travel of grout over long distances was always an item of concern to the engineers in charge of the grouting at Hoover Dam. The travel of grout into the contraction joints did not recur during the program of additional grouting. However, grout did travel extensively through the abutments at times. While holes were being grouted in the Arizona abutment in the area between El. 800 and El. 900, grout leaked from cracks in the concrete lining of the lower penstock tunnel throughout a wet area over 400 ft long in the arch of the tunnel. This grouting resulted in drying a large part of the wet area. While another hole in this same area was being grouted, grout leaked into the tunnel about 200 ft below the hole. This leak was sealed, and the grout travelled upward and broke out through the highway crossing the dam a short distance beyond the abutment.

Mr. Hays also mentions the possibility of cracking concrete by grout pressure in holes drilled through concrete, as was experienced while grouting beneath the upstream toe of the dam. As a result of this experience, it became standard practice to encase all such holes prior to grouting. The USBR later adopted a practice of eliminating the casing and setting a packer in the grout hole in the foundation rock immediately beneath the concrete, thereby preventing the pressure of the grout from acting on the concrete. Satisfactory grout packers had not been developed at the time Hoover Dam was constructed.

Messrs. Hays, Minear, Steele, and Lippold emphasize the necessity of obtaining reliable geologic information. In the construction of large dams, where a large expenditure of money is involved, the full-time services of a

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competent engineering geologist is desirable. However, some underground exploration of the foundation by core drilling is necessary to supplement the geological observations at the surface. In many cases it is the underground conditions not readily discernable at the surface that are the sources of trouble.

Mr. Minear emphasizes the value of uplift pressure indicators at the base of the dam. This relatively inexpensive equipment has proved of great value for giving warning of undesirable conditions not only during the initial filling, but throughout the life, of the reservoir. The installation at Hoover Dam proved to be worth many times its cost during the period of grouting operations, because it was the only means of indicating exactly what conditions were developing as the grouting progressed.

Mr. Minear also calls attention to difficulties that arise when drainage systems are installed in areas where grout leaks may possibly develop. Grout leaks into drains frequently result in impairing the efficiency of the drains or, occasionally, even in rendering them worthless. If no provisions for protection of the drains are made at the time of construction, water may be introduced into them during the period of grouting and, if necessary, held under pressure; or the drains may be flushed at frequent intervals. However, as soon as grout has found its way into a drain, it is likely that its efficiency will never be as great as before it was contaminated.

Regrouting a dam foundation to stop leaks and control uplift pressure can be a most discouraging procedure at times, as Mr. Minear emphasizes. If an open passageway is the source of leakage, it should be plugged adequately when a connection for grouting has been established. Stopping the grouting before the passageway is effectually sealed usually invites future trouble. In view of the possibility of the flow of water carrying the cement grout to the downstream area of the foundation and establishing a cutoff in the wrong place, the following precautions were taken. Before starting the program of additional grouting, a series of drain holes was drilled into the foundation below the downstream toe of the dam from one of the lower galleries in the central section of the power house. The discharge from these drains was checked frequently for indications of grout, but none appeared. This procedure, together with observations of uplift pressure, served to indicate any change taking place in the foundation beneath the dam.

Mr. Steele mentions the value of doing foundation investigation and treatment by force account rather than by contract. The flexibility of procedure provided by a force account crew was advantageous on many occasions when unforseen developments made additional exploration necessary. The ability to continue grouting on a "slow" hole as long as it was felt desirable contributed to better control of the grouting operations. This eliminated such trickery as opening and closing the blow-off valve of the grout supply line under pressure to "slug off" a grout hole, altering pressure gages to show erroneous readings, and mixing the grout insufficiently in order to plug an unprofitable hole with thick grout.

Mr. McAlpine's discussion indicates that the uplift assumptions used in the design of the dam were not clear as stated by the writer. The magnitude of the uplift pressure was assumed to vary as a straight line from full reservoir

pressure at the upstream face to zero or tail water pressure at the downstream face. On the three sections of the dam in Fig. 6, this gradient is shown as "Full Reservoir Pressure Line C." It was further assumed in the design of the dam that the uplift pressures were effective over two thirds of the area of the base. It is realized that the question of the area over which the uplift pressure is effective is subject to a diversity of opinion.[6] The gradient shown in Fig. 6 as "⅔ Pressure B" was used as a warning gradient. When the uplift pressure at a section reached values lying above this line, plans were begun for correcting this condition. Before the additional grouting commenced, however, the uplift pressure exceeded the full reservoir gradient used in the design. The areas of excessive uplift pressure were along the Nevada side of the dam and beneath the downstream toe of the dam under the central section of the power plant.

Mr. Lippold's discussion is a valuable addition to the paper in that it emphasizes the effect of local geological conditions on uplift pressures and upon leakage through the foundation. His comments relative to thorough foundation treatment during the initial construction period, as compared with additional treatment at some later date, are reasonable. He emphasizes the fact that the purpose of the grouting program is to control seepage beneath the dam and that of the drainage program is to relieve pressure.

Mr. Boggess comments on the complex problems encountered in regouting the foundation of a high dam under full reservoir pressure. The difficulties encountered in drilling grout holes that produced large flows of water under pressure are well described. He also explains the use of the uplift pressure gages when grouting with full reservoir pressure against the dam. His discussion emphasizes the necessity of using relatively thin grout mixes in regrouting the foundation rock and cites a typical example of the behavior of grout holes under variations of grout mixes.

It is interesting to note from Mr. Cambefort's discussion that the grouting procedures used in France are based on the same principles as are those used in the United States, but that the two vary somewhat in details. In regard to determining the depth of grout holes used in the original grouting of the foundation of Hoover Dam, the investigation of the foundation treatment of fifty high dams was a study to determine what precedent, if any, existed in the case of extremely high structures. This study was supplemented by field investigations consisting of core drilling twenty-two holes and driving two test tunnels. Information thus obtained was the basis for deciding upon the maximum depth of 150 ft for the original cutoff curtain holes.

The method of precise water testing of sections of an individual hole can serve to determine the depth of that hole in most cases. However, in designing a dam, dependence on water tests only is not advisable. If there are definite geological defects beyond the effective range of the water tests, they should be investigated by a competent geologist and plans should be made for adequate treatment. In the final grouting at Hoover Dam, the section of the grout holes used for determining the depth of the hole in most cases would meet the criteria for permeability set forth by Mr. Cambefort.

There is considerable difference between grouting a limestone foundation that is full of large cracks and a foundation of igneous origin, such as the andesitic breccia at Hoover Dam. In the former case, there is merit in using a grout mixture of cement, clay, sodium silicate, and water intended not to penetrate beyond the foundation area of the dam. In the case of the andesitic formation at Hoover Dam that was subjected to extremely high reservoir pressure, it was necessary to use a thin grout of neat cement and to force it far into the foundation and abutments at times to effect an adequate stoppage of leaks. It is gratifying to have the details of the procedures used in France available for comparison with those used in the United States.

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